Water Recovery from Brines to Further Close the Water Recovery Loop in Human Spaceflight

W. Andrew Jackson[1]
Texas Tech University, Lubbock, Texas, 79409, U.S.A.

Daniel J. Barta[2], Molly S. Anderson[3], Kevin E. Lange[4], Anthony J. Hanford[5], Sarah A. Shull[6]
NASA Johnson Space Center, Houston, Texas,77058, U.S.A

and

D. Layne Carter[7]
NASA Marshall Space Flight Center, Huntsville, AL, 35812

Further closure of water recovery systems will be necessary for future long duration human exploration missions. NASA's Space Technology Roadmap for Human Health, Life Support and Habitation Systems specified a milestone to advance water management technologies during the 2015 to 2019 timeframe to achieve 98% H_2O recovery from a mixed wastewater stream containing condensate, urine, hygiene, laundry, and water derived from waste. This goal can only be achieved by either reducing the amount of brines produced by a water recovery system or by recovering water from wastewater brines. NASA convened a Technical Interchange Meeting (TIM) on the topic of Water Recovery from Brines (WRB) that was held on January14-15th, 2014 at Johnson Space Center. Objectives of the TIM were to review systems and architectures that are sources of brines and the composition of brines they produce, review the state of the art in NASA technology development and perspectives from other industries, capture the challenges and difficulties in developing brine processing hardware, identify key figures of merit and requirements to focus technology development and evaluate candidate technologies, and identify other critical issues including microgravity sensitivity, and concepts of operation, safety. This paper represents an initial summary of findings from the workshop.

I. Introduction

Water is the most critical life support element, representing the largest daily mass input for crew members even under the most stringent water use approaches. A reliable water source is a critical item for long term space habitation, whether in orbit (e.g. ISS), on the moon, Mars or beyond. Effective on-site wastewater recycling eases resupply constraints and can have a cascade effect on mission "utility". Space habitation wastewater can theoretically be composed of a variety of waste streams including urine and associated inputs (flush water and pre-treat chemicals), hygiene (hand wash, shower, oral and shaving), laundry, and condensates (humidity, solid waste drying, etc.). Waste water sources are directly dependent on mission requirements and mission architecture and are largely speculative with the exception of that generated on the ISS. Water recovery hardware for space based waste streams can be separated into primary, secondary and post-processors. Primary and secondary processors remove the bulk of contaminants from the wastewater, and the post-processor "polishes" the product water to meet potable

---

[1] Associate Chair, Civil and Environmental Engineering, 911 Boston, Box 41023
[2] Next Generation Life Support Project Managager, Crew and Thermal Systems Division, Mail Code EC1
[3] Space Technology Principal Investigator, Crew and Thermal Systems Division, Mail Code EC2
[4] ECLSS Systems Analyst, Jacobs Engineering, Mail Code JE-5EA, 2224 Bay Area Blvd, Houston, Texas 77058
[5] ECLSS Systems Analyst, Jacobs Engineering, Mail Code JE-5EA, 2224 Bay Area Blvd, Houston, Texas 77058
[6] Water Recovery Systems Project Manager, Crew and Thermal Systems Division, Mail Code EC3
[7] ISS Water Recovery Systems Lead, ECLSS Development Branch, ES62

water standards, often adding a residual disinfectant. A primary processor is the first step in the treatment process. Secondary processors may be required depending on the quality of the primary processor's product water. A generalized schematic of water recovery system architecture elements is depicted in Figure 1. The Vapor Compression Distillation (VCD) Subsystem, the main component of the Urine Processor Assembly (UPA) on the International Space Station (ISS) is considered a primary processor. It consists of desalination of pre-treated urine and flush water using distillation. Distillate from the VCD is further processed by the multifiltration beds within the Water Processor Assembly (WPA). The multifiltration beds include various adsorption and exchange beds to remove salts and organic contamination, and thus serve as a secondary processor. The WPA's catalytic oxidation reactor serves as a post-processor, removing residual organics and bacteria. The ISS Water Recovery System (WRS) and most other candidate water recovery systems produce byproduct brines which are discarded as waste. The percent of water that is not recovered is variable but could range from perhaps 5-30% depending on the primary water processor system architecture and factors such as waste stream composition, pre-treatment and other variables. Secondary recovery of water lost in brine waste streams could therefore provide a significant mass of water. Depending on the mission, recovery of the water could provide a significant advantage and cost savings.

NASA has supported a number of technology development efforts specifically focused on water recovery from brines. The development of these technologies has been accomplished using a wide variety of waste streams, pre-treatment options, mission scenarios, and assumed primary water processor architectures. In order to insure that future development efforts result in technologies that can be appropriately evaluated and could realistically be incorporated into future missions, it is beneficial to better define or identify the requirements and capabilities of brine water recovery technologies including:

1. Range of brine compositions (including possible pre-treatment compositions) for which technologies should be able to treat.
2. Range of brine processing requirements.
3. Range of acceptable recovered water quality.
4. Range of acceptable recovery efficiencies.
5. Required performance metrics (e.g. energy consumption, consumables, crew time, etc.).
6. Requirements for development evaluation (e.g. can system be tested on ISS).

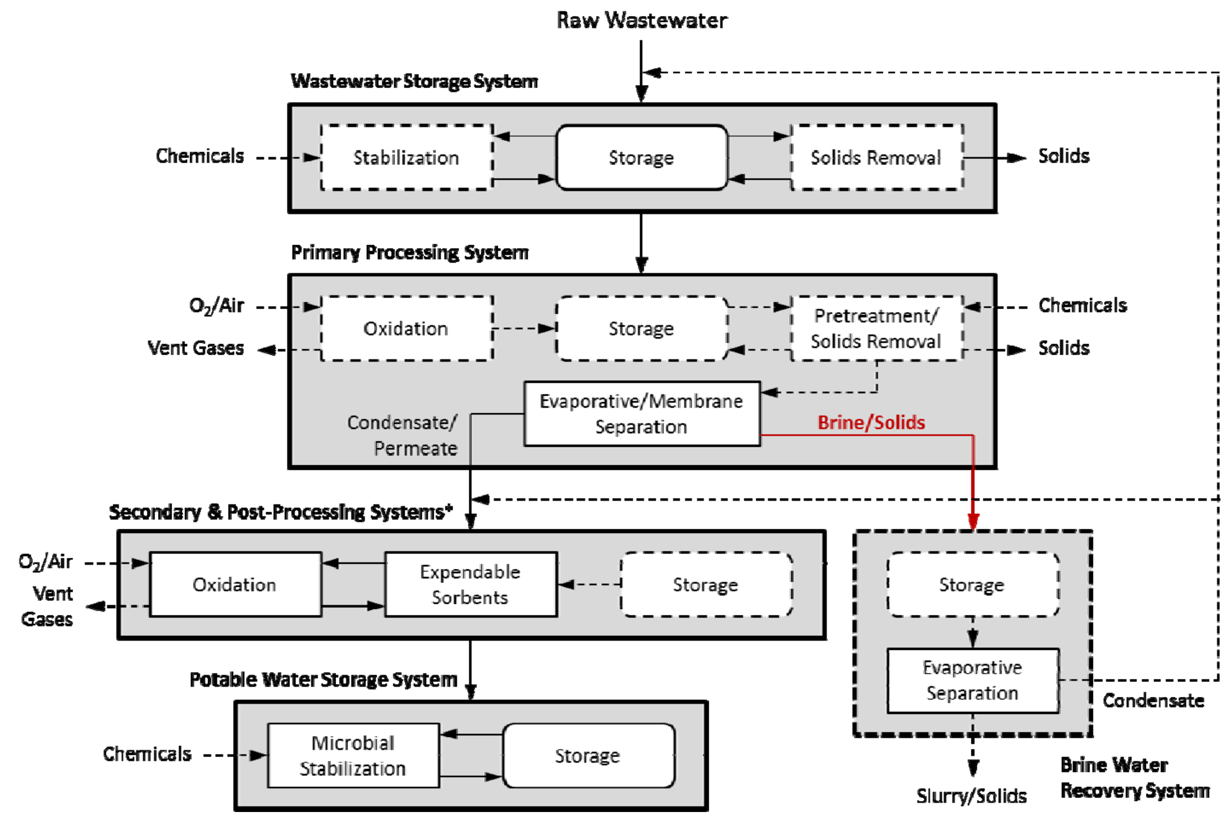

Figure 1. Generalized schematic of water recovery system architecture elements. Elements depicted by dotted lines may be considered optional. *May also be employed as a primary processing system for less contaminated wastewaters.

Prior to initiating any new development efforts, there is a large benefit in developing a community understanding/consensus of all issues (past, present and future) related to water recovery from brines. This maximizes the probability that new efforts will produce the greatest benefit with the least risk. For these reasons a Technical Interchange Meeting (TIM) on the topic of Water Recovery from Brines (WRB) was held on January14-15th, 2014 at Johnson Space Center. The TIM included a large and diverse segment of stakeholders including representatives from NASA's technology development Programs, human spaceflight Programs including the ISS, NASA development/operational engineers, NASA mission analysts, industry and academic community.

The Goal of the TIM WRB was to develop and capture a comprehensive understanding of the issues and needs related to the recovery of water from brine produced by primary water processors (distillation, membrane separation, and biological treatment) in order to better enable future brine processing technology development efforts to increase loop closure of human space habitation wastewater recovery systems.

Specifically the objectives of the TIM were to:

1. Review systems and architectures that are sources of brines and the composition of brines they produce,
2. Review the state of the art in NASA technology development and perspectives from other industries,
3. Capture the challenges and difficulties in developing brine processing hardware,
4. Identify key figures of merit and requirements to focus technology development and evaluate candidate technologies,
5. Identify other critical issues including microgravity sensitivity, and concepts of operation, safety.

This document is a summary of the information and discussion that was presented and occurred during the WRB TIM. The document is organized into major sections including an overview of brine production and sources, brine

treatment requirements and goals, an overview of current brine processing capabilities for treatment of human space habitation waste streams, and issues related to future development and testing.

II. Mission and Architectural Considerations

The benefits and economics of brine water recovery in a spacecraft or habitat Water Recovery System (WRS) have to be addressed at the mission, architecture, and technology levels. Although secondary water processors may be targeted to increase water recovery, it should be kept in mind that technologies that could increase primary water recovery would also meet the overall objective of water balance closure. In general terms, brine dewatering may be advantageous when the mission duration is long enough to justify primary water recovery systems and any of the following are true:

1. The nominal water balance is negative without brine water recovery (quantity of recovered water is less than the water requirement).
2. Brine water recovery is not nominally critical for life support, but is sized such that it can provide dissimilar redundancy for a critical life support function, such as primary water processing or water production by carbon dioxide reduction.
3. Brine water recovery is not critical for life support, but can significantly enhance the mission, for example, by allowing additional extravehicular or hygiene activities.
4. Storage and disposal of brines are highly restricted by crew safety or planetary protection constraints.

Whether a mission duration supports a particular water recovery system must generally be determined by mission-specific and architecture/technology-specific trade studies. A previous reliability-based trade study for a deep-space habitat suggests that water recovery is likely to trade well for operational durations of 180 days or greater (Lange, 2010). This study assumed International Space Station (ISS)-like food/hygiene systems and selected technologies. Shorter break-even times would result from greater water usage. The overall life support system architecture has a strong influence on the water balance. For example, if the system uses stored oxygen and minimal ISS-like hygiene water, a positive water balance is possible without brine water recovery because of water supplied in hydrated food and water produced metabolically by crewmembers (most of which is ultimately recovered). However, if oxygen is generated using water electrolysis or if additional wash water is included, a positive water balance becomes difficult or impossible without brine water recovery. An overall mission-specific cost and reliability analysis is required to determine the optimal level of water closure and the criticality of brine water recovery.

A requirement to store brines will impact mission costs. Adequately constructed storage containers must be provided for short or long term storage of wastewater brines. These containers must be part of the launch mass and will occupy precious volume within the spacecraft. On the ISS, the UPA collects brine in an Advanced Recycle Filter Tank Assembly (ARFTA) Orbital Replacement Unit (ORU). The brine from within the ARFTA is emptied into a Russian ЕДВ container for storage. Each ЕДВ storage container adds 5.5 kg upmass for each 22 liters of brine to be stored or disposed. This corresponds to an additional 25% mass impact to the cost of water in brine that is not recycled. Thus the benefits of recovery of water from spacecraft brines include other savings in addition to the mass of the water recovered.

III. Overview of Brine Sources, Production rates, and Composition

The brine composition and rate of production are directly dependent on the waste water processed, the processes used for primary water recovery, the extent to which the primary waste was concentrated, and the use and type of pre-treatment. These in turn are functions of the mission. In general, potential missions can be evaluated based on their duration, proximity to resupply, and whether they are in space or on a surface with gravity. These could include transit missions of suitable length (e.g. >6 months), habitation outside of LEO, and surface habitats (e.g. Mars and Moon).

A. Wastewater Type and Composition in Relation to Mission

Currently, with the exception of ISS, waste water sources are not well defined. Table 1 attempts to summarize the waste water that could be present based on mission type. All missions able to support water recovery are likely to include humidity condensate and urine as waste water sources, but other significant waste water sources may be

present depending on mission characteristics and trades. These include condensates from carbon dioxide reduction, solid waste drying, and spacesuit humidity control, as well as various types of "wash water" from hygiene (e.g. shower, hand wash, oral hygiene and shaving) and cleaning activities (e.g. laundry). As the architectures for systems that produce or treat these alternate waste streams are unknown, it cannot be necessarily assumed that they would all contribute to brine generation. For example, humidity condensate does not contribute to brine generation on ISS.

Table 1. Summary of potential waste waters that could be present for classes of missions that would likely include water recovery and brine generation.

Mission	Waste Water							
	Urine	Humidity Condensate			CO_2 reduction	Hygiene		Laundry
		Cabin	EVA	Solid Waste Drying		Non-Shower	Shower	
ISS*	√	√	-	-	√	-	-	-
Extended Transit	√	√	-	+	√	+	-	-
Deep Space Habitation	√	√	+	+	√	√	+	+
Surface Habitation	√	√	+	√	√	√	√	√

√ =Likely; + =Maybe; - =Not Likely

These waste waters have widely varying water quality and production rates. Table 2 illustrates the range of constituent values and loading rates for ISS and a potential Deep Space Habitat. The largest contaminant load, both in terms of concentration and daily production, comes from urine, while shower and laundry have the potential to dominate the wastewater volume. In terms of impacts on water recovery from brines, key parameters include volatile components (e.g. organic acids) for their potential to impact cabin air quality, TDS for its impact on solubility and solution thermodynamic properties, organics due to their potential to form sludge rather than crystals, and surfactants for their effect on surface tension and potential to produce foam.

The final parameter that impacts wastewater quality and production is the issue of pre-treatment. On ISS the urine and flush water are pre-treated to reduce microbial activity, urea hydrolysis, and precipitation prior to distillation. This pre-treatment has a major impact on the waste water quality and subsequent brine quality. Missions with launch dates further in the future are more likely to have larger, less concentrated, diverse waste streams and a wider potential treatment architecture, while near term missions would be more likely to have waste streams and architectures similar to ISS and include pre-treatment similar to ISS.

B. Brine Characteristics

The ability/feasibility to recover water from brine is directly related to the quality and quantity of the brine solution. This as previously mentioned is a function of both the primary waste water and water processing technology from which it was produced as well as the type of any pre-treatment used.

Table 2. Production rates and constituent concentrations for various waste waters (adapted from Lange, 2010; Verostko, 2009).

Mission	Waste Water							
	Urine & Flush Water		Humidity Condensate			CO_2 reduction	Hygiene	Laundry
	Pre-Treat	No Pre-Treat	ISS Cabin	Deep Space Habitat[2]	Solid Waste Drying		Non-Shower Shower	
Nominal Load (kg/crew-day)	1.5	1.5	1.95	4.55	0.2	0.75	7.24	8.15
pH	<2	6.5	6-7	7.2	4.4-6.6	7.8	~7	~7
TDS (mg/L)	43,300	37,000	580	600	400	470	960	500

TIC (mg/L)		80		30	NA	70	7	7
TOC (mg/L)	6,900	6,900	450	200	250	2	340	200
TN (mg/L)	10,700	10,700	30	40	30	80	12	12
Major Constituents	Urea, DOC, Cl, Cr, Na, K, SO_4, PO_4	Urea, DOC, Cl, Na, K, SO_4, PO_4	VOCs, Urea, NH_3	Organic acids, NH_4, alcohols, propylene glycol, Zn	Organic acids	HCO_3, NH_4	Surfactants/ Na, Cl, organic acids	Surfactant s/ Na, Cl, organic acids

Impact of waste water sources - The impact of the type(s) of waste waters that contribute to the brine are mainly due to the impact of specific constituents rather than any gross water quality parameter. Hygiene or laundry may have components that impact brine water recovery, such as in the Distillation Comparison Test Solution 2 testing (McQuillan et al., 2010), but their impact on the total mass of TDS, TOC, or TN is relatively small. Table 3 compares the total mass % of TDS, TOC and TN in potential habitation waste waters compared to pretreated urine and flush water. With the exception of TOC for hygiene and laundry waste water no other waste water comprises more than ~10% of the mass in pretreated urine alone.

Table 3. Percent TDS, TOC, and TN mass contribution of various waste streams compared to ISS pretreated urine. Values based on Table 2.

Constituent	Waste Water (% of Pretreated Urine Mass)							
	Pretreated Urine	Urine	ISS Humidity Condensate	HC-DSP	Condensate from Solid Waste Drying	CO_2 Reduction Water	Hygiene	Laundry
TDS	100	88	1	4	<1	<1	11	6
TOC	100	100	2	9	<1	<1	24	16
TN	100	100	<1	1	<1	<1	<1	<1

For example, currently on ISS the primary water processor (UPA) is able to recover ~75% of the water in the pre-treated urine and urine flush water. This limit is due to the potential for precipitation to occur in the brine at higher recoveries (i.e. more concentrated brines). If any other waste stream was combined with the pre-treated urine and flush water, it would only add a relatively small mass of TDS, TOC, and TN so the produced brine would have similar characteristics. This example is only valid assuming that the other waste streams were not pre-treated and limits on solubility are due to $CaSO_4$ precipitates (Muirhead and Carrier, 2012). These limits are not the same for all waste waters. Precipitate formation in pretreated urine is controlled by $CaSO_4$ solubility while for a mixed waste water (Urine, hygiene, and condensate, all pre-treated) specific hygiene products could control the maximum concentration achievable. Pretreatment adds a significant mass of solids (15% of the total TDS in urine) to the waste stream as discussed below. It should also be noted that while the brine produced for any combination of waste streams that include urine would have similar characteristics, the water recovery rate would be higher for treatment of wastewater that includes other non-urine waste streams. Figure 2 illustrates the effect of water recovery on the TDS of the brine theoretically produced from various waste waters. It should be noted that the figure assumes no loss of solids due to precipitation, which is unrealistic at higher recoveries. It also illustrates the residual mass of water remaining in the brine as a function of primary percent water recovery and type of waste water treated. For instance if humidity condensate was added to the urine prior to desalination, 90% of the water could be recovered before achieving the same TDS that would occur for 80% recovery of urine only. Inclusion of humidity condensate, laundry and hygiene would allow >95% recovery before reaching the TDS of urine at 80% recovery. However, significant water as mass would still remain even at 95% water recovery, (0.8L/crew-day compared to ~0.1 L/crew day for the 80% processed urine). In addition, the presence of specific waste water constituents may limit the water recovery rather than $CaSO_4$ solubility for other waste streams. Testing of a pretreated wastewater composed of urine, hygiene, and humidity condensate indicted that a precipitate formed at a TDS well below the TDS at which precipitates formed when distilling only pre-treated urine (Callahan et al., 2012).

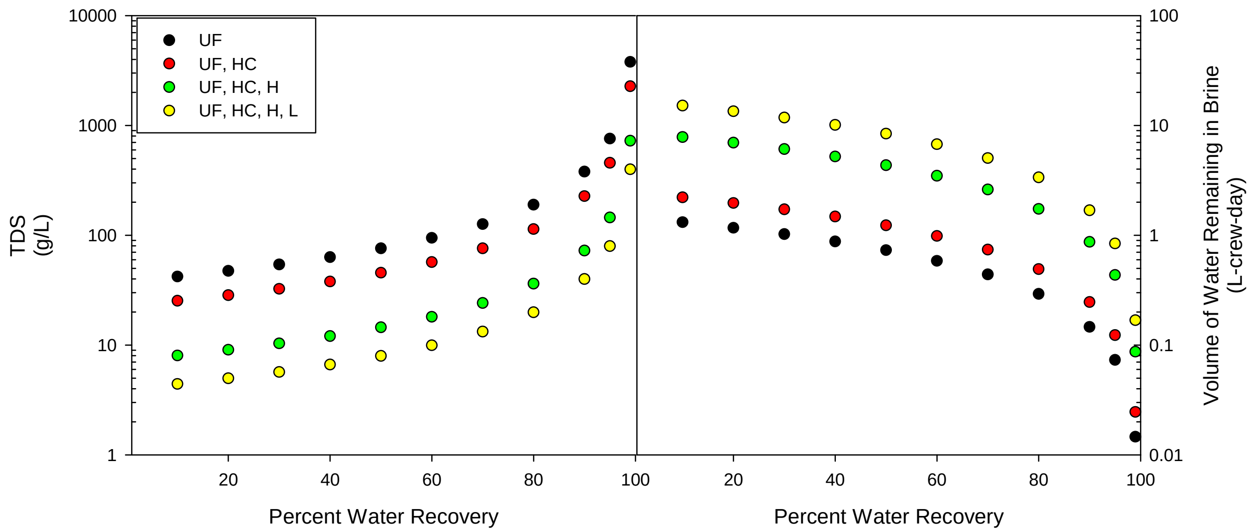

Figure 2. Variation in TDS and volume of water remaining in brine for the complete range of water recovery for various wastewater combinations. (UF=pretreat-urine and flush, HC= humidity condensate, H=hygiene, L= Laundry). Values based on Table 2.

While gross measures of water quality may not significantly change in produced brine, specific components of the other waste streams can have an important impact. Surfactants in the laundry or hygiene water are one such example. The potential impact on surface tension for technologies that rely on hydrophobic/hydrophilic interactions or the potential to generate foam could have significant impacts on the selection of technologies suitable for water recovery from brine.

Impact of Primary Processor - Brine water quality and production rate is dependent on the technology used for primary treatment. In general, the most probable primary processors for future human exploration missions can be grouped into either distillation or membrane technologies. The maximum concentration achievable by current distillation technologies being used or considered for treatment of space habitation waste streams is dependent on the minimum solubility point as they are not able to function if solids form. For membrane desalination systems, final water recovery is likewise dependent on minimum solubility and/or scaling/fouling point unless pressure limits are reached due to osmotic pressure at lower recovery rates. In general, the concentration at which precipitates form should be similar regardless of the primary technology used to treat a given waste water.

Limited data is available regarding brine generation by different technologies. Comparisons are also complicated in that no data on distillation technologies is available for wastewater (urine or urine, hygiene and condensate) that was not pretreated. For membrane technologies, no data is available for pretreated waste streams as they are generally not compatible with pretreatment. In addition, all previous tests that evaluated brine production from membrane based primary processors have included biological treatment while no testing of distillation systems has evaluated biological treatment, which will be discussed later. Keeping in mind the significant differences in composition of the waste streams treated, distillation and membrane primary treatment appear to be able to reach similar recovery rates for similar waste streams. Residual water in brine has varied from 0.225 to 1.1 l/d-crew for wastewaters treated by distillation based on Distillation Comparison Test (DCT) data, (McQuillan et al., 2010). Membrane based systems have produced brine with residual water ranging from 0.875 to1.13 l/d-crew, based on testing at NASA. Residual water is a better measure of recovery, due to the large differences in volumes for various waste water sources. It is unclear whether membrane based systems could achieve higher water recoveries. Water recovery during the Advanced Water Recovery Systems Test (Pickering, et al. 2001; Campbell et al. 2003) was apparently limited by pressure limits on the RO system even though the TDS (13 g/l) was below that commonly treated by terrestrial membrane systems (e.g. sea water = 35g/l). The Alternative Water Processor (AWP) test at Johnson Space Center, that included membrane aerated bioreactors as primary treatment, followed by a forward osmosis/reverse osmosis secondary processor, achieved its goal of 95% recovery (Barta et al., 2014). However, higher recoveries should be possible but were not achieved due to test configurations rather than fundamental issues related to the technology. No comparisons of brine quality as a function of primary treatment (distillation versus

membrane) can be made, due to the large differences in the wastewater evaluated due to biological processing or pretreatment as discussed in detail later.

One critical factor when evaluating past studies or planning future studies is the large difference in strength (e.g. TDS, TOC, and TN) of urine generated in space and that generated in terrestrial studies. In addition, ISS based data is based on 24 hour composite (all urine generated is collected). For terrestrial testing, urine donations are used which often represent the "work day" urine production and so do not include "first voids" which can have significantly higher concentrations of TDS, TOC, and TN. For example, the DCT solution 1 testing reports a TDS solids generation rate of 120 g/d while the solids production rate of ISS is 260 g/d for the same residual water content of the brine. This suggest that the urine used in the DCT solution 1 tests contained less than 50% of the TDS and TOC concentrations (Table 4). A more inclusive analysis also found that concentrations of a wide variety of inorganic and organic constituents were 40-60% lower in the ground based solutions compared to that calculated for flight based concentrations (Figure 3). It should be noted that the DCT solution 1 and 2 testing used a modified pre-treatment (H_2SO_4 and Oxone) rather than the ISS formulation (McQuillan, et al., 2010). Ground based testing should insure that urine is similar in composition to ISS. This can be done by using a urine donation protocol that includes first flushes and/or by increasing the relative volume of urine used and decreasing the volume of flush water to insure that the overall wastewater composition reflects the mass of solids produced based on ISS results.

Table 4. Production rates and properties of brines produced form various distillation and membrane based systems.

Parameter	Data Source				
	Integrated AWRS Test	AWP Test	DCT Solution 1 Testing	DCT Solution 2 Testing	ISS RFTA/EDV Data
Brine Producing Processor	RO	FO/RO	CDS, VCD, WFRD	CDS, VCD, WFRD	VCD
Brine Processor Feed	Bio-Processed Urine, Condensate, Hygiene WW	Bio-Processed Urine, Condensate, Hygiene WW, Laundry WW	Pretreated Urine, Condensate	Pretreated Urine. Condensate. Hygiene WW	Pretreated Urine
Recovery %	~90	~95	93.5	90	70/85
Brine Properties					
Production Rate (l/day)	4.5	3.5	0.9	4.2	1.8/0.9
pH	7.4	6.1	1.7	1.8	2.0
Conductivity (mS/cm)	27	33	104	41	N/A
TOC (g/l)	0.2	0.4	23	6	21/42
TDS (g/l)	13	19	140	45	140/290
TDS (g/day)	60	65	120	180	260

Impact of Chemical Pretreatment or Biological Processing - The inclusion of chemical pre-treatment on biological processing makes the largest impact on the water quality of the produced brine. Pretreatment is practiced to prevent biological growth in the system. The biological growth can lead to flow restrictions and will cause urea to hydrolyze. Urea hydrolyses leads to increased pH and ammonia (NH_3) concentrations that can lead to significant carryover to the polishing system. On ISS urine/flush water to date has been treated using a combination of sulfuric acid and chromium (e.g. ~5 g/L and ~1.3g/l of H_2SO_4 and CrO_3) (Muirhead, 2014). The pretreatment accounts for ~15% of the total TDS in ISS pretreated urine (values based on Table 2). A new pretreatment formulation is currently being developed. It would replace the H_2SO_4 with phosphoric acid (H_3PO_4) and maintain the current CrO_3 dose. The change is intended to allow a higher distillation recovery. Currently the UPA is limited to 75% recovery due to precipitation of $CaSO_4$. The new pre-treatment formulation will allow recoveries up to 87% by replacing the sulfuric acid which accounts for >90% of the total sulfate in the pretreated urine. As previously mentioned, water recovery is limited based on $CaSO_4$ solubility. The replacement of the H_2SO_4 with H_3PO_4 will increase recovery but will lead to an increase in the TDS of the brine due to the higher dose of H_3PO_4 (12 g/L) required. The new pretreatment will account for 27% of the total solids in the pretreated urine. For either formulation, the main effects of the pretreatment on the produced brine are an increase in the TDS, a reduced pH (<2) and the presence of significant concentrations of Cr. It should also be noted that in a number of cases where brine water recovery

technologies evaluated pretreated urine using ISS pretreatment, the final solids were reported to have a "peanut butter" consistency, which was nominally attributed to the H_2SO_4. For future missions that may include treatment of other waste streams by the primary processor (humidity condensates, hygiene, laundry), it is unclear what pretreatment would be required. If these waste streams are pretreated at similar doses to urine, then produced brines would have much higher TDS and lower pH.

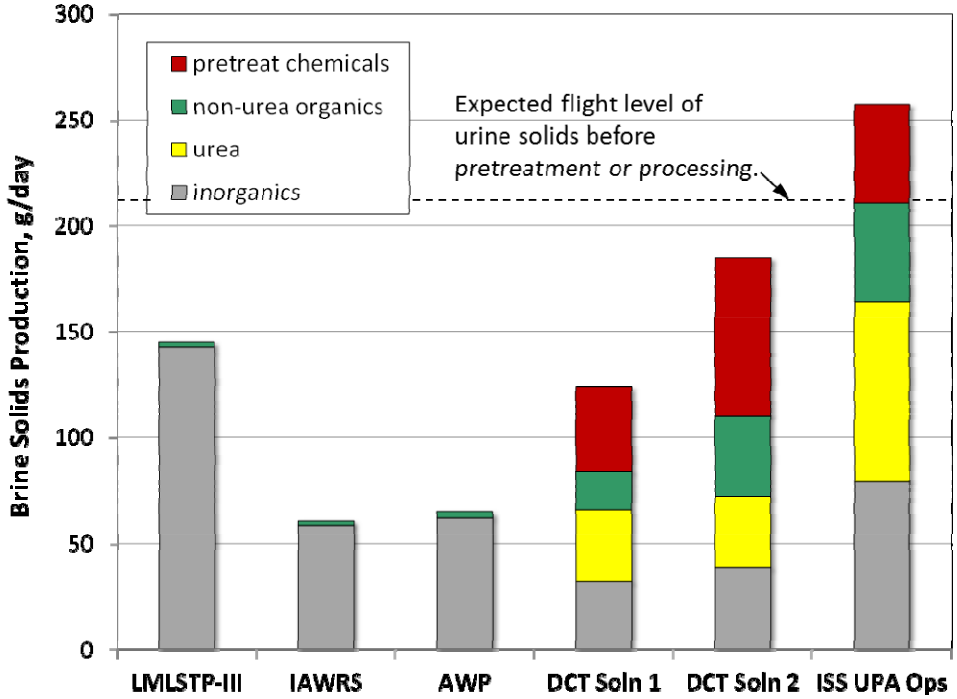

Figure 3. Estimated daily brine solids production and composition. Acronyms and contractions: Lunar-Mars Life Support Test Project (LMLSTP); Integrated Advanced Water Recovery System (IAWRS); Alternative Water Processor (AWP); Distillation Comparison Test (DCT); Urine Processor Assembly (UPA); Solution (Soln); Operations (Ops).

Other pretreatment formulations have been proposed or used in past studies. In the DCT testing, both solution 1 and solution 2 were treated using sulfuric acid (2.3 g/L) and oxone (5 g/L) (McQuillan, 2010). Other pretreatment formulas have been proposed. JSC is in the process of evaluating a "green" pretreatment but at this time no details are available. UMPQUA developed a nonhazardous pretreatment based on quaternary amines, sodium benzoate, and organic acid to lower the pH to ~4 (Akse et al., 2011).

Biological processing as part of primary treatment can also have a substantial impact on brine water quality. Biological processing may preclude the need for pretreatment or in any case is not compatible with current pretreatment formulations or the proposed H_3PO_4 acid based pretreatment. Biological processing can reduce the TOC by >90%, TN by ~50%, leads to almost complete urea hydrolysis, and maintains a pH typically near neutral (6-7.5). The combination of biological processing and lack of pretreatment leads to brines that have much lower TDS (13-19 g/l), TOC (0.2-0.4 g/L), TN (0.7 g/L), and SO4 (1.9 g/L) than brine produced from similar pretreated waste water (TDS = 35 g/L; TOC = 6g/l; TN = 6 g/l; SO4 = 7-15 g/l) (Table 4). Brines produced from biologically treated wastewater allow for inclusion of membrane based primary processors, produce non-hazardous solutions (neutral pH and no Cr), reduce impacts of surfactants on brine dewatering, and may produce better handling consistencies for final dewatered solids. However, it should be noted that alterations in the waste water collection may be required to accommodate the lack of pretreatment and so the inclusion of biological treatment in future missions is unclear.

IV. Brine Treatment Requirements and Goals

The goal of brine treatment is to recover additional water, further "closing the loop", in order to reduce the overall mission costs and increase mission self-sufficiency. The required quality of the produced water is a

secondary issue but can have important consequences if the produced water will have an impact on the overall water treatment process. Many water recovery technologies employ some type of evaporative process, with the transfer of contaminates to the cabin. Impacts to both air quality and the air revitalization system must be considered. The specific goal of any water recovery system from brines will need to be evaluated with respect to the specific mission and cost savings compared to alternate means of providing the same mass of water or redundancy of water supply.

A. Water Recovery Goal and Impact on Brine Dewatering Attributes

Further closure of water recovery systems is recognized throughout NASA and the space community as necessary for future long duration human exploration missions. In their ECLS Capability Roadmap for Exploration, NASA's ECLSS/Thermal Steering Committee identified "additional water recovery from urine or urine brine" as a "functional capability gap" in water management for the ISS, long duration transit microgravity missions and long duration surface exploration missions (Bagdigian et al., 2012). NASA's ECLSS-Environmental Monitoring System Maturation Team (SMT) has identified specific functional gaps and target performance parameters that it believes are essential to enable future human exploration missions (Gatens et al., 2014). Capability gaps identified for wastewater processing included increased water recovery from urine (>85%), reliability, reduced expendables, and dormancy survival. NASA's Space Technology Roadmap for Human Health, Life Support and Habitation Systems (Hurlbert et al., 2012) calls for further closure of high-reliability ECLSS, to >95% O_2 and H_2O recovery from an integrated mission perspective. Increasing the overall water recovery percentage was considered a major challenge. A milestone was specified to advance technologies during the 2015 to 2019 timeframe to achieve 98% H_2O recovery from a mixed wastewater stream containing condensate, urine, hygiene, laundry, and water derived from waste. This later goal can only be achieved by either reducing the amount of brines produced by a water recovery system or by recovering water from wastewater brines. To this end, the National Research Council identified "Water Recovery and Management" as a high priority "Level 3" technology (ASEB, 2012) and Environmental Control and Life Support (ECLS) was identified among eight (8) core technology investment areas within NASA's Strategic Space Technology Investment Plan (NASA, 2012).

While complete water recovery may be possible, it is not necessarily the end goal for all missions. Depending on the mission scenario (see Section V-A) only a portion of the water in brine may need to be recovered. The properties of the brine solution will change as the brine becomes progressively more concentrated. For pretreated urine, the density and viscosity will increase while the specific heat, water vapor pressure, and surface tension will decrease with a decrease in the remaining water content of the brine (Figure 4). In general, most parameters do not significantly start to change until the recovery is >85% for pretreated urine. The onset of significant changes in the property of the brine will also depend on the type of brine due to the large differences in brine quality. Reduction in vapor pressure is significant for pretreated urine brine and increases rapidly as water is recovered, while for BWP/FOST brine over 90% of the water can be recovered before the reduction in vapor pressure is equal to pretreated urine with no vapor recovery. The same trend is true for precipitate production as well. At very high brine water recovery rates, the brine may also exhibit unusual properties. Rather than a suspension or slurry, it has been reported that a paste described as "peanut butter" or "honey-like" in consistency may form. No information was available as to the exact cause of the property but the H_2SO_4 and organic carbon content were suggested as possibilities. For some technologies or brine sources there may be a point at which it is not effective to further concentrate. Assuming 0.225 l/d-crew of pretreated urine + flush water brine generation, approximately 113, 68, and 25 g-crew day of water would be unrecovered at 50, 70, and 90% brine water recovery, respectively. For a 4 person crew it would equate to a resupply need of 164, 98, and 37 kg/year. Final water recovery may also be a function of the ease to which the residual brine and/or solids can be disposed. This is very technology dependent but should be considered.

B. Produced or Recovered Water Quality

The quality of the produced water is dependent on the brine dewatering technology used to produce it. Membrane based systems produce an actual product water, while evaporative technologies recover produced water as condensate either as part of the process or rely on the cabin air processing system. No guidelines are available for the produced water. It is possible that produced water no "worse" than pre-treated urine would be acceptable if the cost is low enough while water similar to humidity condensate would likely be a reasonable goal. The produced water could be treated either by the primary processor or downstream polishing system dependent on its quality. In either case, this load would need to be incorporated into the overall evaluation of the cost of the brine dewatering system. For evaporative systems, the impact on the condensation unit would also need to be evaluated as well as the impact on the air treatment system. Evaporative systems would be expected to potentially transfer significant

volatile components (organic carbon, nitrogen compounds, and inorganic acids). These compounds could increase the required treatment capacity of the cabin air to maintain acceptable quality.

C. Required Processing Rates

Processing rates are primarily defined by the waste streams contributing to the brine. For urine and urine + humidity condensate, processing rates are likely on the order of 0.25-1 liters/crew-day. For habitation waste streams that also include laundry, shower and/or hygiene water the required processing rate may be on the order of 0.8-1.25 liters/crew-day. However, these values do not incorporate the need to integrate with other operations such as brine transfer, storage, or human intervention.

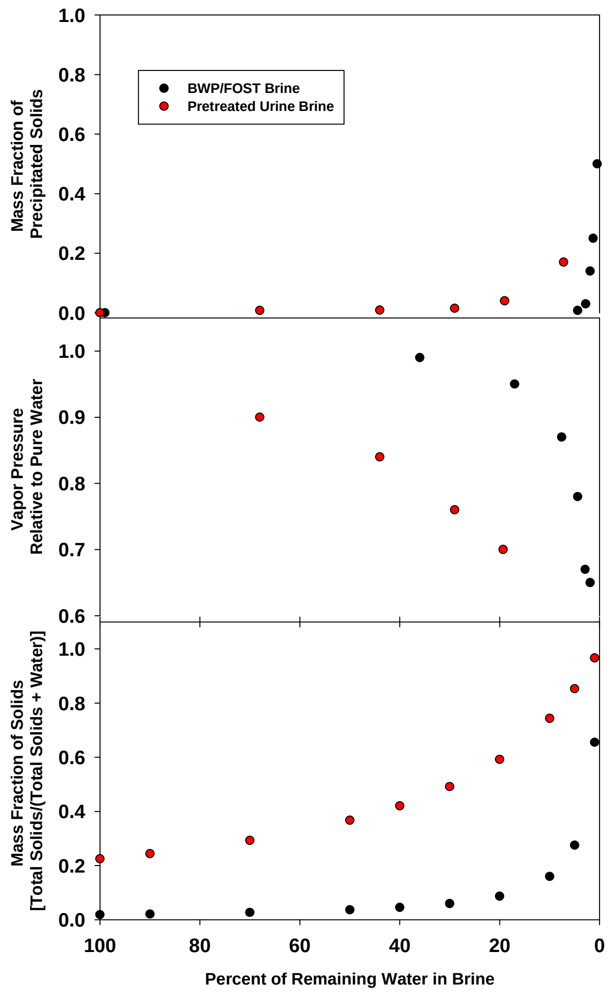

Figure 4. Variation in brine properties as a function of percent water recovered. Data adapted from Putman, 1970.

V. Issues Related to Future Development and Testing

Moving forward NASA will be developing and conducting integrated testing of brine water recovery technologies. Multiple issues related to the input assumptions, methods of evaluation, technology evaluation, and flight testing was discussed. The community should be aware of these issues, although in some cases only NASA will be able to offer final guidelines.

A. Issues related to Process Design and System Integration Assumptions

Development of brine water recovery technologies cannot occur independently of the design mission, overall architecture, and peripheral limitations of system dependent technologies (e.g. air purification system). Several considerations directly limit the allowable development space and are discussed below:

What is the relevant design mission? – In general it would be desirable to develop technologies that can plug and play into relevant missions. However, the reality is that mission specific parameters will always limit the use and/or benefits of proposed technologies. Mission duration directly ties into the degree of recovery that is beneficial, the required volume, and quality of wastewater produced, the presence or absence of other life support related technologies (e.g. the presence of Sabatier or electrolysis), the habitation period and duration when not inhabited, the presence or absence of micro-gravity, and numerous other related issues. Designing technologies that will operate in all conditions is possible but will certainly result in non-optimized operation and performance and in some cases will lead to less robust systems particularly in the case where micro-gravity independent technologies are used for missions where significant reduced gravity is available (e.g. Mars or Moon). A study by Metcalf et al., (2012) developed three generic missions which included: 1) short microgravity exploration missions, 2) long duration microgravity missions, and 3) long duration surface missions. Of these only the second two missions would be applicable to brine recovery. While only NASA can inform the community on the correct design missions, the following are possible examples: 1 Lunar base; 2 deep space habitat at a Lagrange point; 3 long duration transit vehicle; and, 4 Mars surface mission. The design mission will impact the testing and evaluation of brine processing technologies in significant and varied ways. Particularly important are the impacts on inputs, requirements, and integration (discussed below) but also on evaluating the benefits (e.g. payback time or trade analysis) and robustness evaluation.

What are the possible ranges of brines that will be produced? This question is obviously dictated by the answers to the first question. As previously discussed potential wastewater compositions from which brine could be produced have a large range of composition and quality and the brine quality is dependent on the assumed water processor and type of pretreatment. In general, there are two extremes for produced brine. The most challenging is the ISS type pretreated brine (Table 2) as previously discussed, although it does have the lowest required brine processing rate (<0.4 l/d-crew). This brine is the most concentrated, most difficult to achieve 99% water recovery, produces hazardous difficult to handle solids (e.g. sticky consistency), and is highly corrosive. If treatment of this brine is a requirement either in terms of the mission or required development testing (e.g. ISS demonstration) it will likely exclude some technologies based on materials compatibility or dewatering capacity. On the other extreme would be brine produced from a no pretreatment, biologically processed, early habitation base waste stream (e.g. AWP type brine from Table 2). This brine is the least concentrated and the most likely to be compatible with any brine processor, and produces the least toxic waste solids which are easily handled (e.g. better consistency); but may have the largest brine processing rate requirement. Between these two extremes exists a large number of possible combinations. Development of any brine processor must carefully consider the type(s) of brine for which the technology will be applicable. Past testing has evaluated a number of brines that are unlikely to be candidates for future exploration systems. Regardless of the brine evaluated, for any brine derived partially from urine, it is advisable to use real urine rather than ersatz. Ersatz in past testing has not captured the complexity or variability of real urine donations. These variations can have big impacts on performance. Related to this is the importance of using urine of adequate strength. ISS and presumably other urine generated extra-terrestrially is more concentrated both in general and in terms of specific critical components, such as calcium.

What is the upstream and downstream water processing architecture? As previously discussed the upstream architecture will have an impact on the quality and quantity of the brine. But it will also impact future brine processor requirements in numerous other ways. These include the capacity of the condensing heat exchanger, the capacity and performance of the air purification system, how the brine or solids can be transferred, the capacity of the primary water treatment system to handle the return water flow, impact on the trade analysis (can it be used as a backup water processor, what sizing, power, and consumable costs are incurred due to its inclusion), and how does it affect system reliability (interdependence). Development of brine processors which are divorced from likely architectures are likely to lead to technologies that are not appropriate or at best are inefficient.

What is the required output in terms of recovery, rate and quality? As before, these issues are inseparable from the above questions. The recovery will be a function of mission duration and the relative cost of additional recovery versus alternate means of supplying the water (e.g. resupply, in situ utilization). Also of importance will be how the

reliability of the process is impacted by recovery. Required water quality is even more difficult to define. For some missions/architectures produced water quality equivalent to urine may be acceptable while for others humidity condensate quality may be required. It is unlikely that potable water quality would be an endpoint. All water treatment systems will require a polishing system. If the brine processor is meant to be used as a back up to a primary water processor in cases of failure, the produced water quality would need to be equivalent of the primary processor or at least able to meet input requirements for the secondary processor (if present) and the polishing system. The rate of processing will depend on the volume of brine generated per day. Current scenarios range from 0.3 liters/day per crewmember to 1.5 liters/day per crewmember. If the system is to be used a backup for the primary processor then the minimum size would need to produce enough water to meet the oral ingestion requirement (~2 liters/day per crew).

What are the issues related to operation in micro-gravity and how will they be addressed during development? In general all technologies can be impacted by microgravity operational requirements. In some cases these impacts are direct and in others more subtle (e.g. lowered mass transfer due to lack of buoyancy driven convection). If the brine treatment technology is to be used in micro-gravity applications then these impacts need to be addressed throughout the development of the technology rather than after development. The inclusion of development and/or flight engineers familiar with the range of microgravity issues should be a requirement.

What are the hardware requirements? It is not necessary during the technology development for the whole technology to be flight fidelity. However, it is important that critical components including those with possible materials compatibility issues and interfaces have the same fit, form and function and in some cases flight materials. The scale should also be appropriate. Extrapolation from very small scales to full size systems may not be valid. Full scale systems should be required for final test integration.

B. Testing Requirements and Evaluation of Results

Development of brine water recovery technologies cannot occur independently of the design mission, overall architecture, and peripheral limitations of system dependent technologies (e.g. air purification system). Several considerations directly limit the allowable development space and are discussed below:

Mass Balances - One of the critical items that was consistently raised was the need to conduct mass balances on the brine water recovery technologies. This includes not only the water in the brine but also the organic, nitrogen, and inorganic content. It is critical to understand the fate of the various mass fractions. For instance the cost of recovery of a given amount of water from the brine will be very different for a system that transfers significant organic (e.g. volatile organic acids) or nitrogenous (NH_3, or urea decomposition products) residue to the air phase compared to one in which they remain as solids.

Testing Type and Duration - Performance testing needs to include extended duration testing (at least as long as the proposed technology service life). Many issues related to technology reliability and performance may not surface until a significant duration of testing has occurred. These can include materials compatibility, corrosion, biological fouling, material property changes (hydrophobic surface changes), among others. Accelerated testing may not be possible due to interactions of biology and chemistry and impacts of temperature on chemistry. In addition, in order to evaluate the reliability and process consumables, technologies ideally need to be tested until failure or at least as long as the design mission life. Using short testing to extrapolate to long term process rates, water quality, or reliability is likely to be inaccurate. Related to testing duration is also the need to test multiple units. Evaluation of the above parameters based on single units is unlikely to produce data that would allow reliable reliability evaluation or evaluation of performance variability. In cases where subcomponents have been previously tested this may not be necessary but items that are new and particularly those that may be frequently replaced (membranes, wicks, bags) will need to be evaluated for consistency. Testing programs should also include transient start/stop cycles that reflect periods of no habitation either due to extended EVA or periods between missions.

Water quality and air quality parameters from brine processor discharges - While it is important to understand the detailed composition of the produced water and air, it is impractical to test for all possible compounds. At minimum, gross parameters that allow mass balances should be evaluated. For the water phase these might include Total Organic Carbon (TOC), Total Nitrogen (TN), Total Dissolved Solids (TDS), Total Solids (TS), Total Suspended Solids (TSS), Total Fixed Solids (TFS), and should likely also include some major constituents (e.g. Cl^-, NO_3^-, NO_2^- SO_4^{-2}, Na^+, Ca^{+2}, Mg^{+2}, Total P, K^+, NH_3/NH_4, urea or organic N. A more limited number of samples could include

major metals but it is important not to waste resources on excessive water quality testing particularly at early points in the technology development. In cases where particular species are of interest (e.g. evaluation of corrosion, or surfactants) other parameters should be included as needed. Gas phase testing is generally more complex and it is unclear if gross parameters (TOC and TN) similar to those listed above for the water phase can be measured. Certainly specific compound scan be measured such as those evaluated for off-gassing of pretreated urine. But this testing is intensive, costly and may not capture all constituents. It may be possible to measure a subset of critical gasses and then evaluate re-condensed water for the parameters listed above as a way to estimate off gassing.

Energy and Consumables Consumption - At the process scale (brine dewatering test article) the rate of all consumables will need to be determined. In addition, energy usage will need to be quantified in order to allow trade studies. These will need to be developed for appropriate cycles, time periods, and/or design mission life. For brines that include the ISS pretreat method, the cost of triple containment will have to be considered. Technology developers should also include the mass cost of spares. Table 4 lists a number of suggested figures of merit (FOM) that could be used and potential threshold and goal values.

C. Issues Related to Flight Testing

When possible early flight tests should be conducted to evaluate micro-gravity related issues and eventually the final technology will need to be flight tested. A number of issues make these tests challenging. Early stage flight tests focused on performance of system subunits are likely more easily designed and operated as they may be able to use small scale systems and ersatz components to reduce the need to handle ISS pretreated brine. For instance possible tests could include the impact of concentration polarization for membranes, operation of spray dryers, wick loading, performance of ultrasonic nebulizers, or capillary control of bag or liquid wetting surfaces. Handling of the brine will be a significant issue due to the safety concerns and difficulty in the transfer of the solution. Return samples may also be problematic as there will be significant safety concerns in case of a hard landing and possible rupture of contained liquids. Final flight testing may be the biggest hurdle. For systems not designed for an ISS system even if compatible with ISS brine, there may be no way to flight test on ISS unless a completely independent system is flown. Systems designed for ISS integration may not meet mission requirements for other design missions. NASA will need to direct the appropriate development path but care should be taken that current ISS requirements do not prevent the development of technologies that could significantly improve the overall water processor performance and enable human exploration.

Table 4. Candidate Figures of Merit (FOM), units, threshold and goals for future brine water recovery technologies. Values were developed in break-out sessions during the Brine TIM and are only illustrative.

Figure of Merit	Units	Notes
Specific System Mass (System and consumable mass/Water)	kg/kg	ISS Value (~5:1)
Breakeven Time	Days	Depends on Mission
Specific Crew Time	Hours/kg	ISS ~1 hr/month; Goal Value = 0.
Product Water Quality (TOC, TN, TDS)	mg/kg	Threshold: Able to be reprocessed by primary processor (urine equivalent); Goal: Able to be processed by polishing system. (e.g. humidity condensate)
Complexity (numbers of sensors, components, powered components)	N=#	Not yet determined
Specific Energy	W-hr/kg	Threshold Value = 1,300 (2-3 times latent heat of vaporization); Goal Value = 660 (Latent heat of vaporization)
Specific Consumable Mass (Water/Consumable/Water)	kg/kg	Threshold Value = 0.25; Goal Value = 0.1
Specific System Volume	liters-day/kg	Not yet determined
Water Recovery Rate	kg/kg	Threshold Value = 0.99 (Based on 90% water recovery from EPB waste stream brine @ 90% primary water recovery); Goal Value = 0.96 (Based on

		100% water recovery form pretreated urine)
Water Production Rate	kg/d-crew	Threshold Value = 0.3; Goal Value = 2.0
Gas Phase Quality	kg/kg and g/m^3	Threshold Value = < SMAC; Goal Value = < UPA.
Specific Waste Mass and Volume	kg-day/kg and liter-day/kg	Not yet determined
ESM	kg	Depends on Mission
Feed Robustness	Types	Threshold Value = ISS; Goal Value = All Feeds

VI. Examples of Technologies for Recovery of Water from Brines

Over the last 20 years, NASA has supported a number of technology development efforts specifically focused on water recovery from brines. Technologies can be loosely grouped into 4 process technology types: aerosol dryers, wick evaporation, membrane systems, and bulk or surface drying. Most technologies are at generally low (<5) Technology Readiness Levels (TRL), although at least one technology, the Air Evaporation System, was extensively evaluated in integrated water recovery systems testing, including human-in-the-loop tests (Pickering and Edeen, 1998; Campbell et al., 2003). Example technologies, for which citable references are available, are listed in Table 5.

Table 5. Examples of process technologies for recovery of water from brines.

Type of Process/Title of Technology	References
Aerosol Dryers	
Water Reclamation using Spray Drying	(Coppa et al., 2011)
Brine Dewatering Using Ultrasonic Nebulization	(Akse et al., 2011)
Wick Evaporation	
Air Evaporation System	(Pickering et al., 2001; Smith et al., 1999, Campbell et al., 2003)
Advanced Air Evaporation with Reusable Wicks	(Akse et al., 2012)
Membrane Systems	
Brine Evaporation Bag (BEB)	(Delzeit et al., 2012)
Ionomer-Membrane Water Processor System	(Kelsey et al., 2012).
Bulk or Surface Drying	
Brine Residual In-Containment (BRIC)	(Callahan et al., 2012).
Enhanced Brine Dewatering System	(Remiker, et al., 2009)
Lyophilization for Water Recovery	(Litwiller, et al., 2001, 2004, 2005; Wheeler, et al., 2007)

Brief descriptions these process technologies are given below. Additional information will be included in the final report for the Technical Interchange Meeting or can be obtained from the cited references.

Water Reclamation using Spray Drying - Brine is sprayed into a drying chamber using an ultrasonic nozzle (Coppa et al., 2011). The drying chamber is a volume in which a drying medium is simultaneously passed. The drying medium is air or N2 gas. The drying medium is heated to between 100 and 200°C. The water is evaporated from the brine droplets and carried as vapor to a condenser. The "dry" solids are separated from the drying medium by a cyclone separator. It should be noted that the cyclone separator is not intrinsic to the brine drying process and could be replaced by other appropriate solid air separators. The technology incorporated the use of proprietary nano-powders. The nano-powders were used to aid in the solids drying process. Without the nano-powders the solids formed a "peanut butter" consistency making it very difficult to manipulate residues. Incorporation of the powder at an appropriate dose (1-5%) produced a dry powder.

Brine Dewatering Using Ultrasonic Nebulization - Ultrasonic waves are used to create micron-sized aerosols (Akse et al., 2011). An ultrasonic transparent wicking material is used to maintain the brine at the nebulizer surface. The brine aerosols are dried under a partial vacuum at air temperatures 115°C. Heating of sweep gas was accomplished using a resistive heater in testing, but other methods were proposed (infrared, microwave). A bag filter, disc filter, cyclone separator, and electrostatic precipitator were proposed or evaluated for solids removal.

Air Evaporation System - Wicks made from polyester urethane foam and/or polyester felt are used to evaporate brine. Brine can be injected into the wick or into a reservoir in which the end of the wick sits. The brine is

transferred through the wick by capillary action. The wick contains holes through which heated air can be passed through. Evaporated water is collected by condensation. Wicks are used until their capacity is exhausted and then replaced. This technology has been the most extensively tested and optimized including multiple long term integrated tests (Pickering and Edeen, 1998; Smith et al., 1999; Pickering et al., 2001; Campbell et al., 2003).

Advanced Air Evaporation with Reusable Wicks - Ceramic felts, fibers, or fabrics heated to 50-70°C are loaded with brine by capillary action and water is evaporated from the wick in a drying chamber by passing heated air across the wick (Akse et al., 2012). Water vapor can then be condensed. Once the wick is fully loaded it can be heated at high temperatures to oxidize/volatilize the organic and N component. The wick can then be reloaded with brine and the cycle repeated until the wick loading capacity is reduced beyond acceptable limits. At this point the wick can be loaded with hot water to dissolve the precipitates and partially regenerated allowing additional loading cycles.

Brine Evaporation Bag (BEB) - A nonporous bag with sidewalls composed on hydrophobic membranes (Delzeit et al., 2012). Water vapor/steam can pass through the membrane but not liquid water. The bag is filled with brine and heated under a partial vacuum. An air sweep removed the water vapor from a custom drying chamber composed of multiple vacuum ports and heaters with separate temperature controls. The bag can be used for multiple drying cycles until its solids holding capacity is reached or the membrane resistance becomes unacceptable.

Ionomer-Membrane Water Processor System - A bag composed of a Nafion membrane layered with a hydrophobic filter material (ePTFE) is filled with wastewater (Kelsey et al., 2012). The hydrophobic filter prevents direct contact between the Nafion membrane and wastewater but allows water vapor to migrate to the Nafion membrane. The Nafion membrane acts to allow water vapor migration for evaporation from the bag exterior surface but also acts as a barrier to some gasses. The bag can be heated but it is not required. Sweep gas is required which could also be heated.

Brine Residual In-Containment (BRIC) - This technology concept focuses on brine drying in the container used for final disposal (Callahan et al., 2012). The brine is placed in a container and subject to a heat source under a partial vacuum. The water evaporates and is removed from the sweep gas by condensation. The heat source can be placed above the liquid surface (e.g. heat lamp) or below the liquid surface as a heating element. The liquid brine is maintained in the correct container location by either capillary forces or by rotating the container. After evaporation additional brine can be added and the process repeated until the container is filled to capacity with solids. The disposable container is then sealed and replaced.

Enhanced Brine Dewatering System (EBDS) - The Enhanced Brine Dewatering System (EBDS) was developed to allow nearly complete recovery of water from Lunar Outpost wastewater brines (Remiker et al., 2009). The system is gravity dependent. The EBDS concept involves a cycle of depositing brine onto a rotating solid substrate, evaporating the water from the brine, and scraping the residual solids from the substrate. This cycle repeats continuously as fresh brine is deposited after solids are removed from the substrate. The water that evaporates from the brine is then condensed and collected, with a portion of the heat of condensation used to reheat the air that evaporates the brine. Testing was completed for the brine application system, the dried solids removal and collection system, and the thermal transfer system. A full system prototype EBDS was assembled and provided to NASA.

Enhanced Brine Dewatering System (EBDS) - The Enhanced Brine Dewatering System (EBDS) was developed to allow nearly complete recovery of water from Lunar Outpost wastewater brines (Remiker et al., 2009). The system is gravity dependent. The EBDS concept involves a cycle of depositing brine onto a rotating solid substrate, evaporating the water from the brine, and scraping the residual solids from the substrate. This cycle repeats continuously as fresh brine is deposited after solids are removed from the substrate. The water that evaporates from the brine is then condensed and collected, with a portion of the heat of condensation used to reheat the air that evaporates the brine. Testing was completed for the brine application system, the dried solids removal and collection system, and the thermal transfer system. A full system prototype EBDS was assembled and provided to NASA.

Lyophilization for Water Recovery - In the lyophilization process, water in an aqueous waste is frozen and then sublimed, separating the waste into a dried solid material and liquid water (Litwiller, et al., 2001, 2004, 2005; Wheeler, et al., 2007). The systems operate under vacuum or very low pressure. Energy necessary for sublimation of ice is provided by heaters or microwave power. The water vapor is subsequently collected as relatively pure ice on a condenser, which may be a thermoelectric cooler or a more conventional condensing heat exchanger. Benefits of microwave power include efficient energy transfer and selective heating of water by direct absorption of electromagnetic radiation, thus minimizing conductive and convective losses, and reducing drying times relative to more conventional freeze drying processes.

Several lessons learned from these technology development activities include:

- Relatively high temperatures used for some methods of drying may cause urea degradation within brines that contained urine in the original wastewater source.

- Warm moist conditions may encourage growth of mold or other microorganisms when dewatering brines derived from wastewater for which no pretreatment was added. This growth may affect materials or system characteristics such as hydrophillicity.
- Pretreated brines may not dry into a crystalline powder, but may become pasty and or syrupy and difficult to handle. Addition of nanomaterials or other agents can improve the consistency of these brines as they dry.
- Brines, especially those that contain pretreatment chemicals, are highly toxic and corrosive and will require attention to materials selection, operational considerations and additional levels of containment for the safety of crew and equipment.
- Water recovered from brines, including condensates, may include considerable dissolved organics and acid gases which need to be considered during further processing steps.
- Gas streams and gaseous byproducts produced by brine water recovery processes need to be fully characterized. It cannot be assumed that brine processors can be directly vented to the spacecraft cabin.

VII. Summary

A Technical Interchange Meeting (TIM) on the topic of Water Recovery from Brines (WRB) was held on January14-15th, 2014 at Johnson Space Center. Advancement of brine dewatering technologies was seen as a critical step toward achieving NASA's goal to achieve 98% H_2O recovery from a mixed wastewater stream during the 2015 to 2019 timeframe. The TIM reviewed sources of brines and their composition, the state of the art in NASA technology development, captured the challenges and difficulties in developing brine processing hardware, identified key figures of merit and requirements to focus technology development and evaluate candidate technologies, and identified other critical issues including microgravity sensitivity, concepts of operation, and safety. This conference report represents an initial summary of the TIM. Additional information will be available in a full report to be released at a future date. It is hoped that information generated from this TIM will be used by decision makers to initiate new investments in this important technology area.

References

Akse, J. R., & Wilson, G. A. (2012). Advanced Air Evaporation System with Reusable Wicks for Water Recovery.

Akse, J., Holtsnider, J. T., Wheeler Jr, R. R., & Fisher, J. W. (2011). Brine Dewatering Using Ultrasonic Nebulization. In 41st International Conference on Environmental Systems.

Akse, J. R., Williams, T. W., Hadley, N. M., & Dahl, R. W. (2011). Nonhazardous urine pretreatment method for future exploration systems.

ASEB (2012). NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space. Steering Committee for NASA Technology Roadmaps, Aeronautics and Space Engineering Board, National Research Council (NRC), The National Academies Press, Washington DC.

Bagdigian, R., Carrasquillo, R., Metcalf, J., Peterson, L. (2012) National Aeronautics and Space Administration (NASA) Environmental Control and Life Support (ECLS) Capability Roadmap Development for Exploration. GLEX-2012.10.1.1x12284, Global Space Exploration Conference, May 22-24, 2012, L'Enfant Plaza Hotel, Washington, DC.

Barta, D.J., Chullen, C., Pickering, K.D., Meyer, C., Cox, M., Aitchison, L., Flynn, M., Wheeler, R., Jackson, W.A., and Abney, M. (2014). Next Generation Life Support Project Status. 44th International Conference on Environmental Systems Paper #253.

Callahan, M., Pensinger, S., & Pickering, K. (2012). Preliminary Feasibility Testing of the Brine Residual In-Containment (BRIC) Concept. 42nd International Conference on Environmental Systems, San Diego, CA. Paper AIAA 2012-3526.

Campbell, M.L., Finger, B.W., Verostko, C.E., Wines, K.R., Pariani, G. M. and Pickering, K. D., (2003), Integrated water recovery system test. 33rd International Conference of Environmental Systems, Vancouver, BC, Paper Number 2003-01-2577.

Coppa, N. V., Milani, A. M., & Fardig, D. A. (2011). Reduction of brine to dry solids using nanopowder drying agents. 41st International Conference on Environmental Systems, Portland, OR. Paper ," AIAA 2011-5172.

Delzeit, L., Fisher, J., Pace, G., & Shaw, H. (2012). Brine Evaporation Bag Design Concept and Initial Test Results. In 42nd International Conference of Environmental Systems, San Diego, CA. Paper AIAA-2012-3525.

Gatens, R.L., Broyan, J.L., Macatangay, A.V., Metcalf, J.L., Shull, S., Bagdigian, R.M., and Stephan, R. (2014). National Aeronautics and Space Administration (NASA) Environmental Control and Life Support (ECLS) Technology Development and Maturation for Exploration: 2013 to 2014 Overview. 44th International Conference on Environmental Systems, 13-17 July 2014, Tucson, AZ, Paper Number 19.

Hurlbert, K., Bagdigian, R., Carroll, C., Jeevarajan, A., Kliss, M., Singh, B. 2012. NASA Space Technology Roadmap, Human Health, Life Support and Habitation Systems, Technology Area 06, TA-06, April 2012, NASA, Washington, DC.

Kelsey, L., Straus, J., & MacCallum, T. (2012). Employing ionomer-based membrane pair technology to extract water from brine. In 42nd International Conference on Environmental Systems.

Lange, K.E., Water Architecture Study (2010) ESCG-4470-10TEAN-DOC-0161
Litwiller, E., Reinhard, M., Flynn, M., and Fisher, J. (2001). Lyophilization for Water Recovery. In 31st International Conference of Environmental Systems, Orlando, Florida. Paper Number 2001-01-2348.
Litwiller, E., Flynn, M., Fisher, J. and Reinhard, M. (2004) Lyophilization for Water Recovery II, Model Validation. In 34th International Conference of Environmental Systems, Colorado Springs, CO, Paper Number 2004-01-2377.
Litwiller, E., Reinhard, M., Fisher, J. and Flynn, M., (2005). Lyophilization for Water Recovery III, System Design. In 35th International Conference of Environmental Systems, Rome, Italy. Paper Number 2005-01-3084.
Metcalf, J, Peterson, L., Carrasquillo, R., and Bagdigian, R. (2012) National Aeronautics and Space Administration (NASA) Environmental Control and Life Support (ECLS) Capability Roadmap Development for Exploration. 37th International Conference of Environmental Systems, San Diego, CA. Paper AIAA 2012-3444
McQuillan, J., Pickering, K. D., Anderson, M., Carter, L., Flynn, M., Callahan, M., ... & Yeh, J. (2010). Distillation Technology Down-selection for the Exploration Life Support (ELS) Water Recovery Systems Element. In 40th International Conference on Environmental Systems, Barcelona, Spain.
Muirhead, D. and Carrier, C. (2012) Comparison of Four Strong Acids on the Precipitation Potential of Gypsum in Brines during Distillation of Pretreated, Augmented Urine: Preliminary Results. 37th International Conference of Environmental Systems, San Diego, CA., Paper AIAA-2012-3528
Muirhead Pretreatment Solution for Water Recovery Systems. United States Patent Application Number 14/252,660 filed on 2/20/2014
NASA (2012). NASA Strategic Space Technology Investment Plan, National Aeronautics and Space Administration, Washington DC, December 5, 2012.
Pickering K. and Edeen M., (1998) “Lunar-Mars Life Support Test Program Phase III Water Recovery System Operation and Results”, 28th International Conference on Environmental Systems, Danvers Massachusetts, SAE Technical Paper 981707.
Pickering, K.D., Wines, K.R., Pariani, G.M., Franks, L.A., Yeh, J., Campbell, M.L., Finger, B.W., Versostko, C.E., Carrier, C., Gandhi, J.C., and Vega, L.M. (2001). Early results of an integrated water recovery system test. 31st International Conference on Environmental Systems, Orlando, FL. Paper Number 2001-01-2010.
Putnam D. F., (1971) Composition and Concentrative Properties of Human Urine, NASA/CR-1802, McDonnell Douglas Astronautics Co., Huntington Beach, CA.
Remiker, R.W., Marten, A.M., Zelle, B.C., and Hunter, J.B. (2009) Development of an Enhanced Brine Dewatering System. In 39th International Conference of Environmental Systems, Savannah, GA. 2009-01-2486.
Wheeler, R.R., Hadley, N.M., Dahl, R.W., Williams, T.W., Zavala, D.B., Akse, J.R., and Fisher, J.W. (2007) Microwave Enhanced Freeze Drying of Solid Waste, 37th International Conference of Environmental Systems, Chicago, IL. SAE Technical Paper 2007-01-3266.

Nomenclature and Acronyms

AWP	=	Alternative Water Processor
AWRS	=	Advanced Water Recovery System
BWP	=	Biological Water Processor
kg	=	kilograms
°C	=	degrees centigrade
DCT	=	Distillation Comparison Test
CDS	=	Cascade Distillation System
EDV	=	Russian Water Storage Container
EPB	=	Exploration Planetary Base
FOST	=	Forward Osmosis Secondary Treatment
g, g/l	=	grams, grams per liter
VCD	=	Vapor Compression Distillation
WFRD	=	Wiped-Film Rotating Disc
DCT	=	Distillation Comparison Test
DOC	=	Dissolved Organic Carbon
FO	=	Forward Osmosis
FOST	=	Forward Osmosis Secondary Treatment
HC	=	Humidity Condensate
hr	=	Hour
ISS	=	International Space Station
L, l	=	Laundry, Liters
l/d	=	Liters per day
mg/l	=	milligrams per liter
mS/cm	=	milli-siemens per centimeter

N/A	=	Not Applicable
RO	=	Reverse Osmosis
TDS	=	Total Dissolved Solids
TFS	=	Total Fixed Solids
TIC	=	Total Inorganic Carbon
TN	=	Total Nitrogen
TS	=	Total Solids
TSS	=	Total Suspended Solids
TOC	=	Total Organic Carbon
TIM	=	Technical Interchange Meeting
UF	=	pretreated urine and flush
UPA	=	Urine Processor Assembly
VOC	=	Volatile Organic Carbon
W	=	Watt
WRB	=	Water Recovery from Brines
WRS	=	Water Recovery System
WW	=	Wastewater